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PRELIMINARY STUDY OF OPTIMUM DUCTBURNING TURBOFAN ENGINE CYCLE DESIGN PARAMETERS FOR SUPERSONIC CRUISING

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Preliminary Study of Optimum Ductburning Turbofan Engine Cycle Design Parameters For Supersonic Cruising

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SUMMARY

A study has been made of the effect of turbofan engine overall pressure ratio, fan pressure ratio, and ductburner temperature rise on the engine weight and cruise fuel consumption for a Mach 2.4 Supersonic Transport. A practical engine must be designed to accomodate all of the mission requirements, including for example off- design operation at takeoff with noise constraints and subsonic cruise. However, this study is limited to consideration of design- point engines that are optimized purely for the supersonic cruising portion of the flight, where the bulk of the fuel is consumed. The purpose of the study is to provide an idealized benchmark against which more- practical engines can be measured.

This study concludes that, based on constant thrust requirements at cruise, (fixed gross weight and aerodynamics), fuel consumption considerations would favor medium- bypass ratio engines (1.5 to 1.8) of overall pressure ratio of about 16. Engine weight considerations favor low bypass ratio (0.6 or less) and low overall pressure ratio (8). Combination of both effects results in bypass ratios of 0.6 to 0.8 and overall pressure ratio of 12 being the overall optimum. In addition, ductburning is shown to be desirable in reducing engine weight with acceptable fuel consumption penalties.

INTRODUCTION

It is well known that, for long-range subsonic cruising, the optimum jet propulsion system is a high bypass ratio, high overall pressure ratio turbofan (refs. 1 & 2). On the other hand, it is usually stated that the optimum supersonic propulsion system is a low bypass ratio turbofan (or even a turbojet), with fairly low overall pressure ratio (refs. 3 to 5). However, even a supersonic aircraft must takeoff, accelerate, and cruise subsonically (if only for hold and divert, if not for extended overland flight) plus satisfy low noise requirements (for commercial use). Hence, a compromise system for both adequate subsonic and supersonic performance is necessary. Another approach is a variable cycle engine (VCE) that can convert from one mode of operation to another as required during flight. Thus, under the NASA/SCAR (Supersonic Cruise Airplane Research) program, Pratt & Whitney and General Electric have identified concepts that can accomplish this to a greater- or- lesser degree (refs. 6 to 12).

The presently proposed VCE concepts are limited in their ability to vary their operating characteristics, often require their components to operate off design and thus at less than maximum efficiency, and generally suffer weight penalties to achieve their variability. So there is a continuing motivation to search for new concepts that more nearly approach the ideal of optimum performance both subsonically and supersonically. As an aid in this search, it was thought useful to examine the optimum design- point engine parameters for the purely supersonic cruising condition, in order to provide a benchmark against which the various VCE concepts can be compared.

The candidate engine cycle to be optimized is a separate flow ductburning turbofan operating at a maximum turbine inlet temperature limited by the assumed level of technology. The influence of bypass ratio, fan pressure ratio, overall pressure ratio, and ductburner temperature on fuel consumption and engine weight is then computed for a representative Mach 2.4 SST airplane. The effects of varying turbine rotor inlet temperature (RIT) and the use of mixed flow afterburning turbofans are also indicated.

ANALYSIS

The basic engine cycle studied here is the ductburning turbofan. Dry and mixed flow afterburning turbofans are included for comparison. Component performance such as inlet recovery, and fan, compressor, burner, and turbine efficiencies are assumed to be about equal to those used by GE and P&W in their contracted SCAR engine studies. Since only supersonic cruise performance is considered, it is not necessary to employ off- design performance maps for each component.

The thermodynamic performance of the engine is calculated with the Navy/ NASA Engine Program (NNEP) (ref. 13). The WATE1 engine weight computer code, developed by Boeing (ref. 14), is used to calculate engine weight. The WATE1 program functions as a part of the NNEP cycle analysis code. The optimization capability of NNEP is used to determine the best fan pressure ratio (FPR) and ductburner outlet temperature as engine bypass ratio (BPR) and overall pressure ratio (OPR) are varied.

compressor bleed air is used to cool the high and low pressure turbines. Bleed flow requirements are based on 1990 technology levels as built into the NNEP code. High pressure turbine rotor inlet temperature (RIT) is 3160 °R while coolant flow temperature varied with FPR and OPR. The effect of varying RIT is shown. A complete list of engine cycle performance assumptions and mechanical design assumptions for weight calculations are presented in Tables I and II respectively and the Symbol List in Table III.

The WATE1 engine weight code uses a preliminary design plus correlation approach to predict engine weight. Thus, stress levels, temperature, material, geometry, stage loading, hub-tip ratios, and shaft speeds all enter into the calculation procedure. As FPR, OPR, and BPR are varied, the number of fan, compressor, and turbine stages change. Thus this approach fairly accurately shows what happens to the engine weight as engine parameters are varied.

This report will not attempt to do a complete mission analysis of an SST. Takeoff, climb, transonic operation, etc. are being ignored. The only portion of the mission being considered is the supersonic cruise where most of the fuel is consumed. It is therefore possible to just set thrust equal to drag (gross weight divided by lift to drag ratio) and calculate fuel by the Brequet range equation:

$$R = \frac{V\,L/D}{SFC} \ln\left(\frac{1}{1 - W_f/W_g}\right)$$

For this simple situation, a convenient measure of propulsion system performance is to calculate the minimum of the sum of engine weight and fuel weight.

In order to calculate fuel consumption, an aircraft with a lift to drag (L/D) ratio of 9.0 is assumed. The present study involves both constant airflow engines (700 lb/sec) and constant thrust engines (4 @ 20000 lbf each). For constant thrust, the airplane weighs 720 000 lb. at the start of cruise. Since engine weight and fuel weight vary as functions of the engine cycle, payload will also vary and will be a maximum when the engine plus fuel weight is a minimum. The airplane is flown 4000 statute miles on a standard day at constant L/D at Mach 2.4 to evaluate fuel consumed. Initial cruise altitude is 54 000 feet.

RESULTS AND DISCUSSION

In a typical SST, fuel may be the largest single weight component, sometimes as much as 40 percent of the gross weight. This would suggest that minimization of the specific fuel consumption (SFC) to give minimum fuel is of paramount importance. Figure 1 shows how engine design parameters affect uninstalled SFC. The data are for engines without ductburning since ductburning in all cases increases SFC.

As can be seen from this figure, the SFC minimizes or becomes relatively flat at a bypass ratio, shown by the dashed lines, of about 1.5 to 1.8 . The best overall pressure ratio for low SFC, shown by the solid lines, is about 16 . The minimum with OPR occurs as a result of increased bleed requirements as the temperature of the turbine cooling air increases with OPR.

This figure also shows that the percentage change in SFC over the entire range of BPR and OPR is on the order of only 5 percent while changes in thrust per unit airflow (F/Wa) vary by as much as a factor of 2. Hence, for a given required cruise thrust, Wa will vary greatly with OPR and BPR and so will the engine weight which varies strongly with the airflow.

The variation of engine weight per unit thrust as a function of OPR and BPR is shown in figure 2. The engine weight as used in this report does not include the inlet, nacelle, and engine mounts. It does include the nozzles and frames. This figure is for 700 lb/sec airflow engines with no ductburning. Note should be made here that the values of Wengine/F are only valid for this airflow, ie. the engine weight will not scale linearly with airflow. From this figure we see that low Wengine/F occurs at low OPR and low BPR. Thus for a given required thrust, the lowest engine weight occurs when the engine has the highest SFC (recall figure 1), and this engine weight can vary by as much as a factor of 2.

Since payload for an SST of any specific gross weight would be arrived at by subtracting the sum of engine plus fuel weight from a constant, we must therefore consider both of these weights when determining the optimum cycle parameters for SSTs. Furthermore, since the variation in engine weight now can be as important as variation in fuel consumption, we can consider the possibility of trading off a decrease in engine weight against an increase in SFC by allowing for ductburning.

This tradeoff of SFC and engine weight with ductburning is shown in figure 3. Only four of the OPR-BPR combinations are shown for clarity. These are sufficient to indicate the trends. The circled point to the left on each curve represents the duct temperature as a result of the compression process through the inlet and fan; there is no fuel being burned in the duct. Every point to the right of the circle represents a varying degree of ductburning. As can be seen from the two parts of the figure, for all combinations of OPR and BPR, SFC increases with ductburner temperature and weight of the engine per unit thrust decreases.

At the dry points, SFC decreases with increasing OPR and/or BPR while engine weight per unit thrust decreases with decreasing OPR and/or BPR as previously shown. However, at high DBT (ductburner temperature), it is observed that the high OPR/BPR combination tends to have poorer SFC.

Let us now consider the case of the representative SST previously described. We have assumed a 720 000 lb airplane at the start of cruise. The mission requires a cruise of 4000 miles at a constant L/D of 9. As discussed previously, since fuel weight and engine weight vary as functions of the engine cycle, payload will also vary and will be a maximum when engine plus fuel weight is a minimum. Since the L/D is 9, the total thrust required is 80 000 lb or 20 000 lbf/engine for a 4 engine aircraft.

The bare engine weight and fuel weight for this airplane is shown in figure 4. As can be seen by the solid lines, which represent dry engines, fuel weight decreases with BPR and OPR while engine weight increases with BPR and OPR. Ductburning cases are shown by the dashed lines in the figure. In all ductburning cases, the ductburner temperature and the fan pressure ratio are optimized to minimize the sum of engine plus fuel weight. The optimum temperature varied between 1600 and 1700 °R. Engine weight still increases with BPR and OPR but is significantly less than that for the dry engines. Fuel weight is higher than that for the dry engines and appears to minimize at BPRs of 0.8 to 1.1 and an OPR of about 16.

The sum of the engine plus fuel weight is shown in figure 5. Each ductburning engine is better than the corresponding dry engine. The OPR optimizes in the 12 to 16 range with a relatively flat minimum in total weight at BPRs of 0.6 to 0.8 . The optimum fan pressure ratio varies between 2.2 and 2.7 with low FPR at high BPR and high FPR at low BPR. Thus, the addition of engine weight and the use of ductburning into the cycle parameter selection process has driven us to to lower OPR and BPR contrary to what we would have selected on a pure SFC basis. However, it is notewothy that the total change in engine plus fuel weight is very small (2-3 percent) over a wide range of variations in OPR and BPR provided that DBT and FPR are re-optimized in each case. Non-optimum FPRs, as long as they are in the range of 2.2 to 2.7, can vary these results by less than 5 percent.

As previously mentioned, the engine weight as used herein does not include nacelle or inlet weights. These weights are strong functions of total engine corrected airflow. This airflow is shown in figure 6 for the 20 000 lbf thrust engines. As expected, corrected airflow is seen to increase with BPR and OPR and ductburning reduces required engine airflows by as much as 50 percent. Nacelle friction drag will also be a function of engine airflow size. Figure 7 shows the effect of nacelle friction drag on engine plus fuel weight. (Only friction drag is considered, as pressure drag can usually be mitigated by area- ruling the airframe.) Also shown is the "best" OPR curve from figure 5 (no nacelle drag). As expected, the nacelle drag results in higher fuel plus bare engine weight (by about 4000 lbs.). The shape of the curves are essentially unchanged from those of figure 5; namely, BPR should be on the order of 0.6 to 0.8 and OPR of 12 to 16. If the two figures are overlaid and the scales shifted, it would be seen that the inclusion of nacelle drag does tend to drive the minimum to very slightly lower BPR. Including inlet and nacelle weights would enhance this tendency. Typically these weights would add an additional 30 to 60 percent of the bare engine weight which, recalling figure 4, would heavily affect the high BPR cases and thus shift the optimum towards low BPR. This is illustrated in figure 7 for the OPR 12 case by assuming a 45 percent value of inlet plus nacelle weight.

Up to this point we have only looked at dry and ductburning separate flow turbofans. Shown in figure 8 is the performance of mixed flow afterburning turbofans. As can be seen from the figure, the afterburning cases as indicated by the dashed lines are essentially insensitive to BPR (less than 2000 lbs. variation along any OPR line). OPR optimizes at lower values than for the ductburning engines (shown by the solid lines) being 8 to 12 rather than 12 to 16. The ductburning engine appears to be superior but only by 8000 lbs. or less than 4 percent. Inclusion of other factors favoring afterburning mixed flow engines such as friction and boattail drag might easily overcome this difference. FPRs must be lower for static pressure balance in the mixer of the afterburning engines and optimize in the 1.4 to 1.9 range with the low FPR at the high BPR and vice versa.

The effect of the rotor inlet temperature (RIT) on the performance of the separate flow ductburning turbofan is shown in figure 9. Raising the RIT 100 °F is only significantly effective at high OPRs which are non- optimum anyway. Increased cooling requirements diminish the expected gain. These levels have increased by about an additional 4 percent of the compressor exit air, the absolute values of course varying with OPR and FPR. Optimum BPR again is in the 0.6, to 0.8 range and, at a BPR of 0.6 OPRs of 12 to 20 give approximately the same fuel plus bare engine weight requirements. Of course, if new turbine materials come along which allow for higher RIT without the need to increase coolant flow higher RIT will appear more beneficial.

Figure 10 shows the effect of a variation in cruise Mach number on optimum engine design. The L/D of the airplane is assumed to be 10.9 at this Mach number of 2.0 yielding a required thrust of 18500 lbf./engine. The optimum OPR again is on the order of 12 and the optimum BPR around 0.8 . An OPR of 8 appears to be better than an OPR of 16 contrary to what was found for the Mach 2.4 study. At this lower Mach number, the corrected flow of the engine for the required thrust is higher than that required at Mach 2.4 . Since the engines are being sized and weighed at cruise in this study, and the size of the engine is dictated by corrected flow rather than actual flow, engine weights are higher. (Fuel consumption is lower). But, recall from figure 2 that low engine weight is obtained at low OPR. This shifts the optimum results at Mach 2.0 to the lower OPR values.

All of the engines studied herein have only been operated at the design point of supersonic cruise. The actual airplane cannot be designed solely on the basis of optimum supersonic cruise. Takeoff, climb and acceleration, and the presence of any significant subsonic leg will exert an influence on optimum cycle selection. The optimum engine, for example, for best low- speed performance per the Energy Efficient Engine studies has a BPR of 7 to 10, OPR of 35 to 45 and FPR of 1.5 to 1.8 (ref. 1). This difference in the two designs explains the great interest in Variable Cycle Engines.

A further complication is the need for a civilian SST to satisy engine noise limits, jet noise being extremely troublesome during takeoff. Since jet noise is proportional to Vj (exponentially) and Vj is proportional to F/Wa, low noise tends to require low F/Wa. But low F/Wa (from fig. 1) occurs at high BPR and OPR. (Fig. 1 is for supersonic cruise, but the trends are the same for takeoff.) This question of cycle selection for noise cannot be pursued further without establishing the relationship between takeoff and cruise which would require full off- design calculations using component maps and is beyond the scope of this report.

CONCLUDING REMARKS

This analysis has shed light on some primary tradeoffs involved in engine selection for supersonic airplanes. These effects can be summarized by: SFC considerations lead to dry turbofan engines of BPR greater than 1, and engine weight considerations favor low bypass engines with ductburning.

For simplicity this study has only considered bare engine weight and fuel consumption on the supersonic cruise portion of the mission. Other factors that have not been incorporated in this study can change the optimum engine selection.

Other factors that should be considered include: inlet and nozzle matching at all the operating conditions throughout the flight; engine off- design performance; engine/ airframe integration; aerodynamic and structural compromises due to incorporating variable cycle features; etc. - all of which are being done by the NASA SCAR contractors. Complete missions must be simulated to identify the sizing criteria both for the engines and the airframe. This report does provide a reference point with which to compare the necessarily compromised real engines.

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TABLE I- Engine Cycle and Cooling Assumptions

Inlet- Recovery	0.932	
Fan- Adiabatic Efficiency	0.840	
Compressor- Adiabatic Efficiency	0.872	
Main Burner- $\Delta P/P$	0.062	
Adiabatic Efficiency	1.000	
Fuel HV	18400	BTU/lb.
HPT- Rotor Inlet Temperature	3160	°R
Adiabatic Efficiency	0.891	
LPT- Adiabatic Efficiency	0.917	
Ductburner- $\Delta P/P$	0.032	
Adiabatic Efficiency	0.995	
Cooling Type- Full coverage film		
Design Lifetime	10000	hrs.
Technology Year	1990	

TABLE II- Engine Mechanical Assumptions

Fan-	Face Mach Number	0.6
	Maximum 1st. stage PR	1.7
	h/t	0.35
	solidity	1.5
	AR 1st stage	4.0
	AR Last stage	3.0
	Exit Mach Number	0.4
	Blade material density	0.12 lb./cu.in.
	Constant Mean Radius	
Compressor-	Face Mach Number	0.57
	Maximum 1st. stage PR	1.5
	h/t	0.7
	solidity	1.1
	AR 1st stage	2.5
	AR Last stage	1.0
	Exit Mach Number	0.3
	Blade material density (Ti or steel)	0.168/0.286 lb./cu.in.
	Constant Mean Radius	
Primary Burner-	Thruflo vel.	100 ft./sec.
	Residency Time	0.015 sec.
HPT-	Superalloy	0.286 lb./cu.in.
	Face Mach Number	0.4
	Loading Parameter	0.28
	Solidity	1.4
	AR throughout	1.7
	Exit Mach Number	0.5
	Constant Hub	
LPT-	Superalloy	0.286 lb./cu.in.
	Face Mach Number	0.5
	Loading Parameter	0.253
	Solidity	1.3
	AR 1st stage	4.0
	AR last stage	6.0
	Exit Mach Number	0.6
	Constant Hub	
Core Nozzle-	L/D	2.8
Bypass Nozzle-	L/D	1.45
Ductburner-	thruflo velocity	150 ft./sec.
	Residency Time	0.015 sec.
LP & HP shafts-	density	0.3 lb./cu.in.
	Allowable Stress	50000 lb./sq.in.

TABLE III- Symbol Table

BPR-	Bypass Ratio
FPR-	Fan Pressure Ratio
F/Wa-	Thrust per Unit Airflow - lb/(lb/sec)
L/D-	Lift to Drag Ratio
OPR-	Overall Pressure Ratio
R-	Range - ft
RIT-	Rotor Inlet Temperature - °R
SFC-	Specific Fuel Consumption - lb/(lb/sec)
SST-	Supersonic Transport
V-	Aircraft Velocity - ft/sec
VCE-	Variable Cycle Engine
Vj-	Jet Velocity - ft/sec
Wf-	Fuel Weight - lb
Wg-	Aircraft Gross Weight - lb

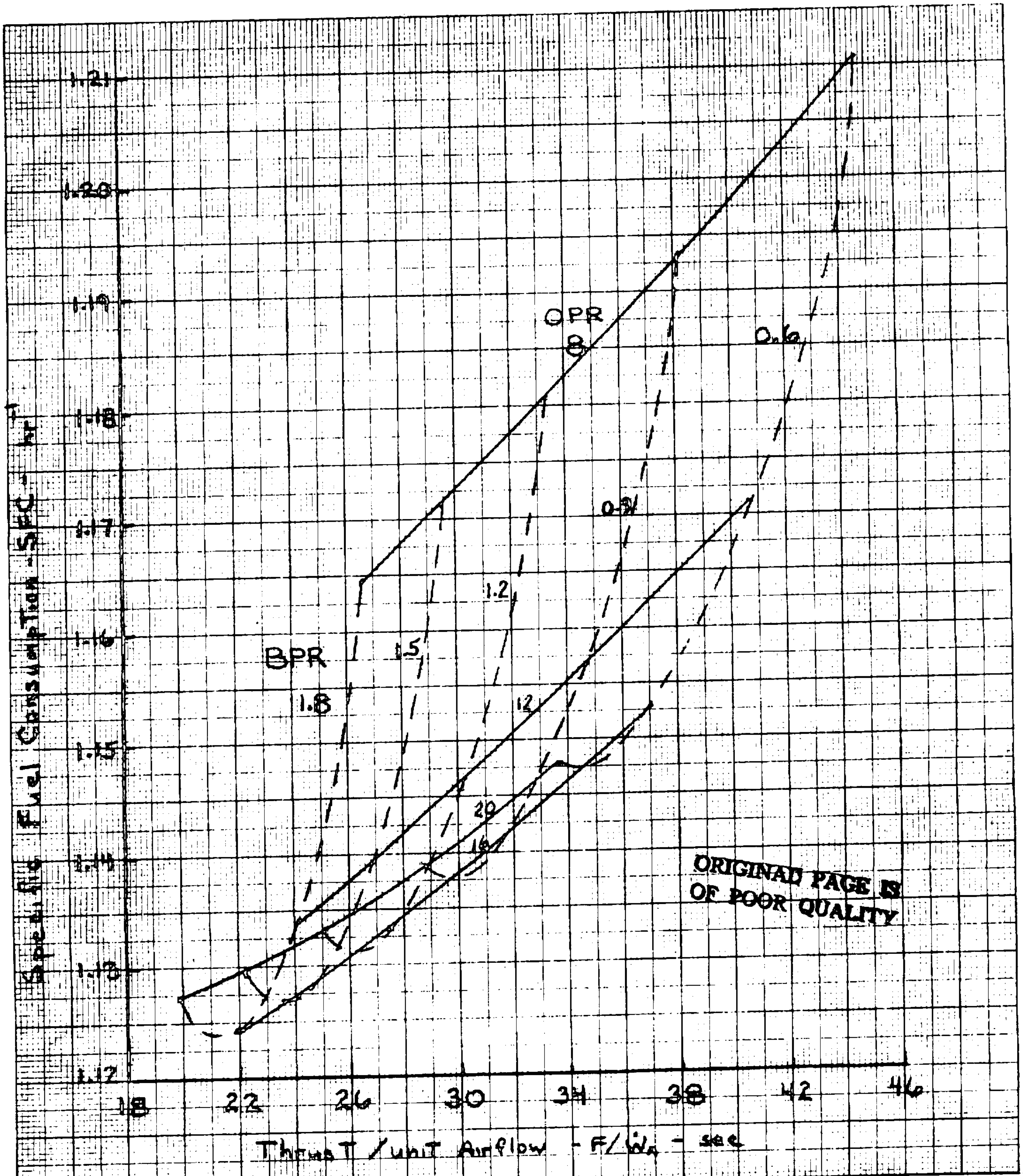

Fig. 1: Engine Specific Fuel Consumption as a function of Engine Thrust per Unit Airflow. Mach 2.4, 54000 ft., No Ductburning, Fan Pressure Ratio optimized for minimum SFC.

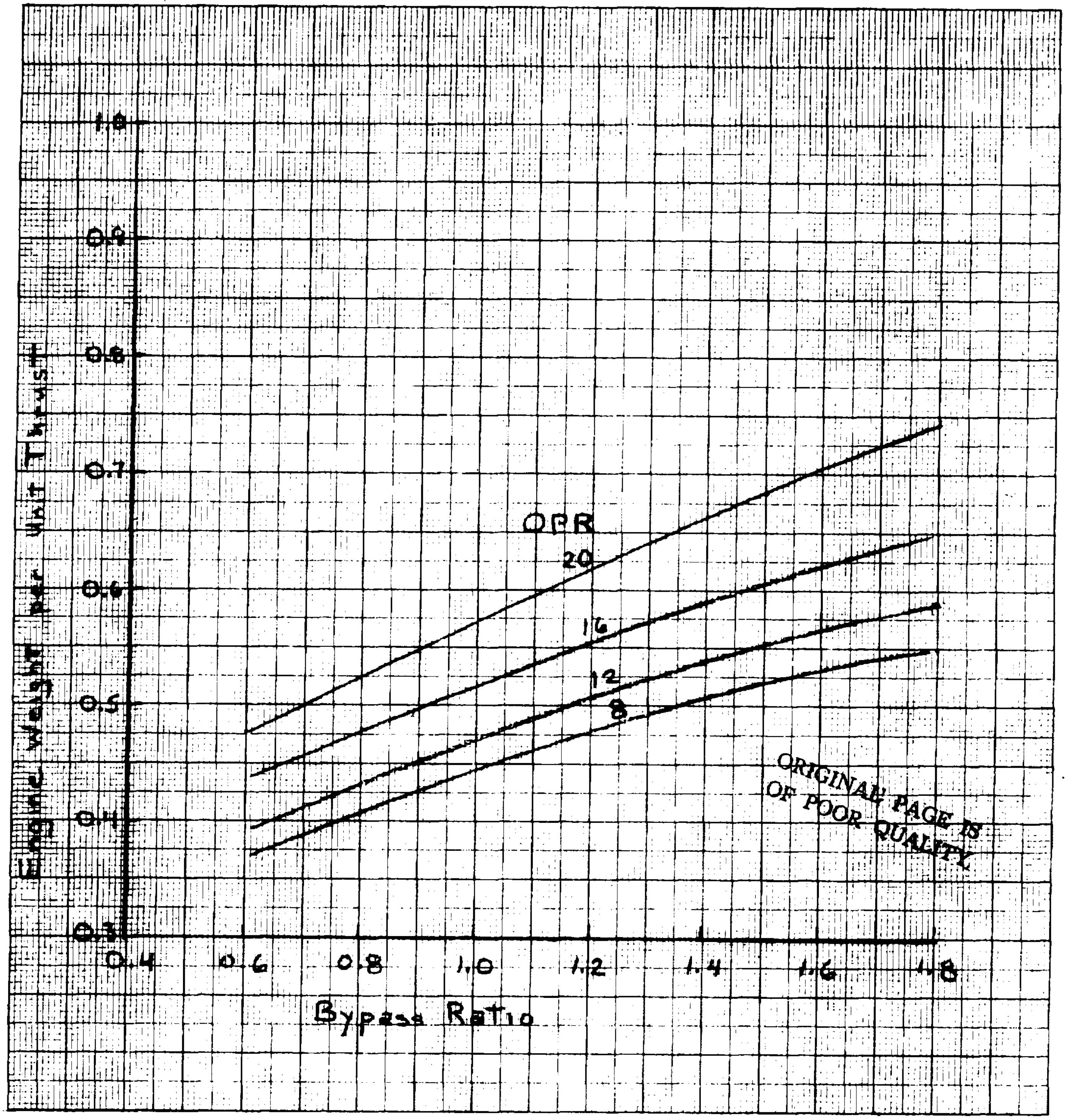

Fig. 2: Engine Weight per Unit Thrust. 700 lb./sec. engines.

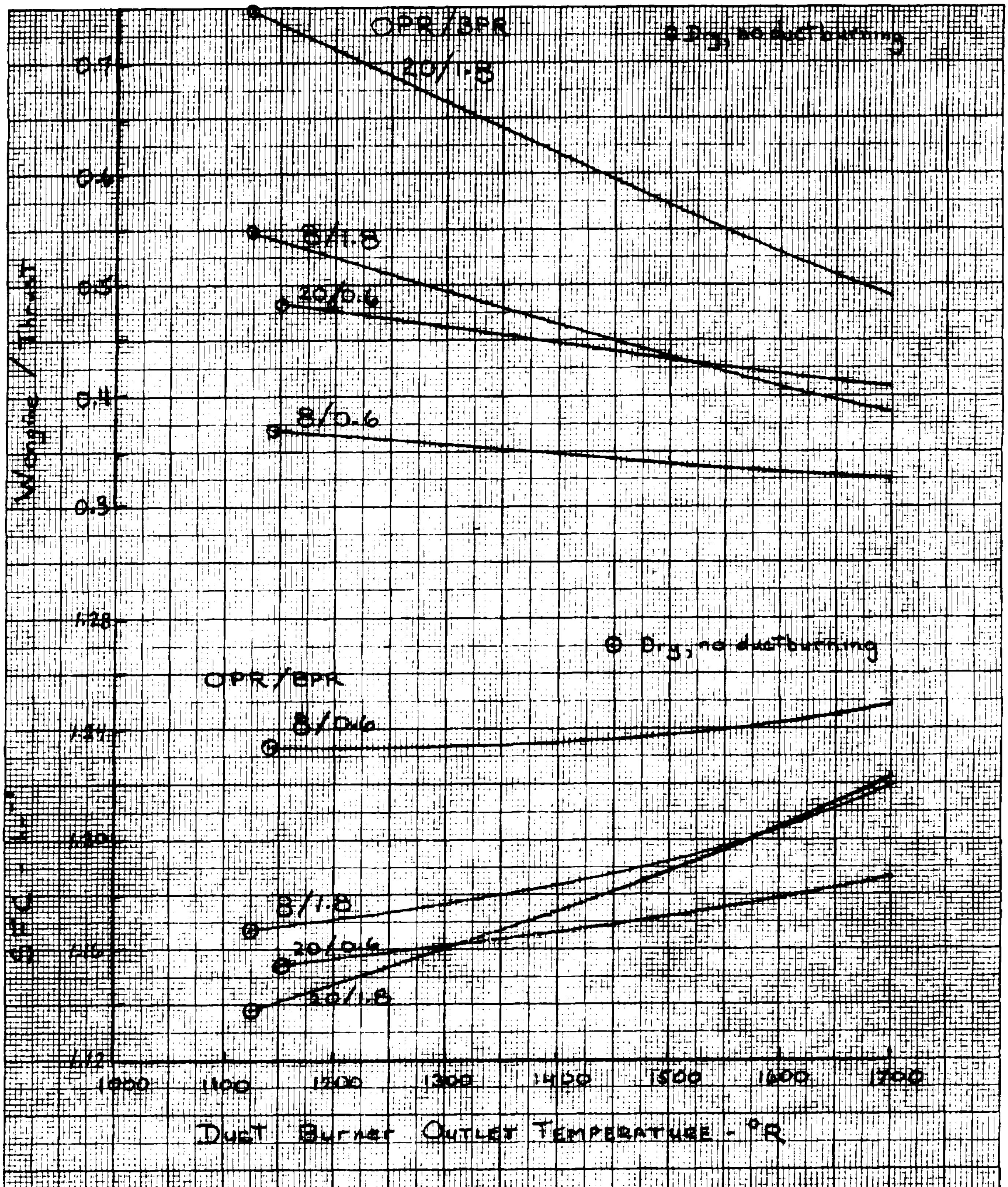

Fig. 3: Effect of Ductburning on Engine Weight per Unit Thrust and Specific Fuel Consumption. 700 lb./sec. engines.

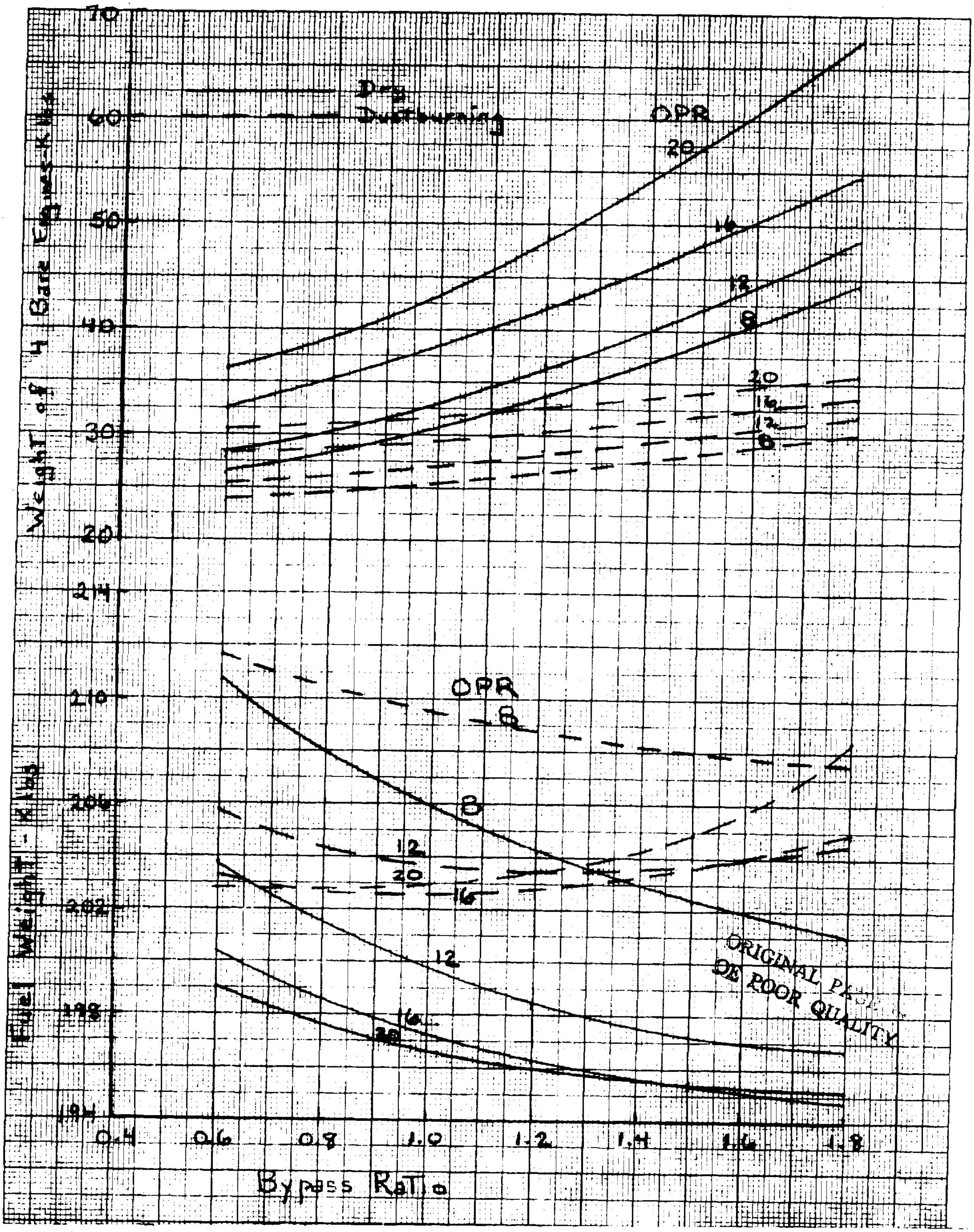

Fig. 4: Fuel Weight and Bare Engine Weight. 20000 lb. thrust engines.

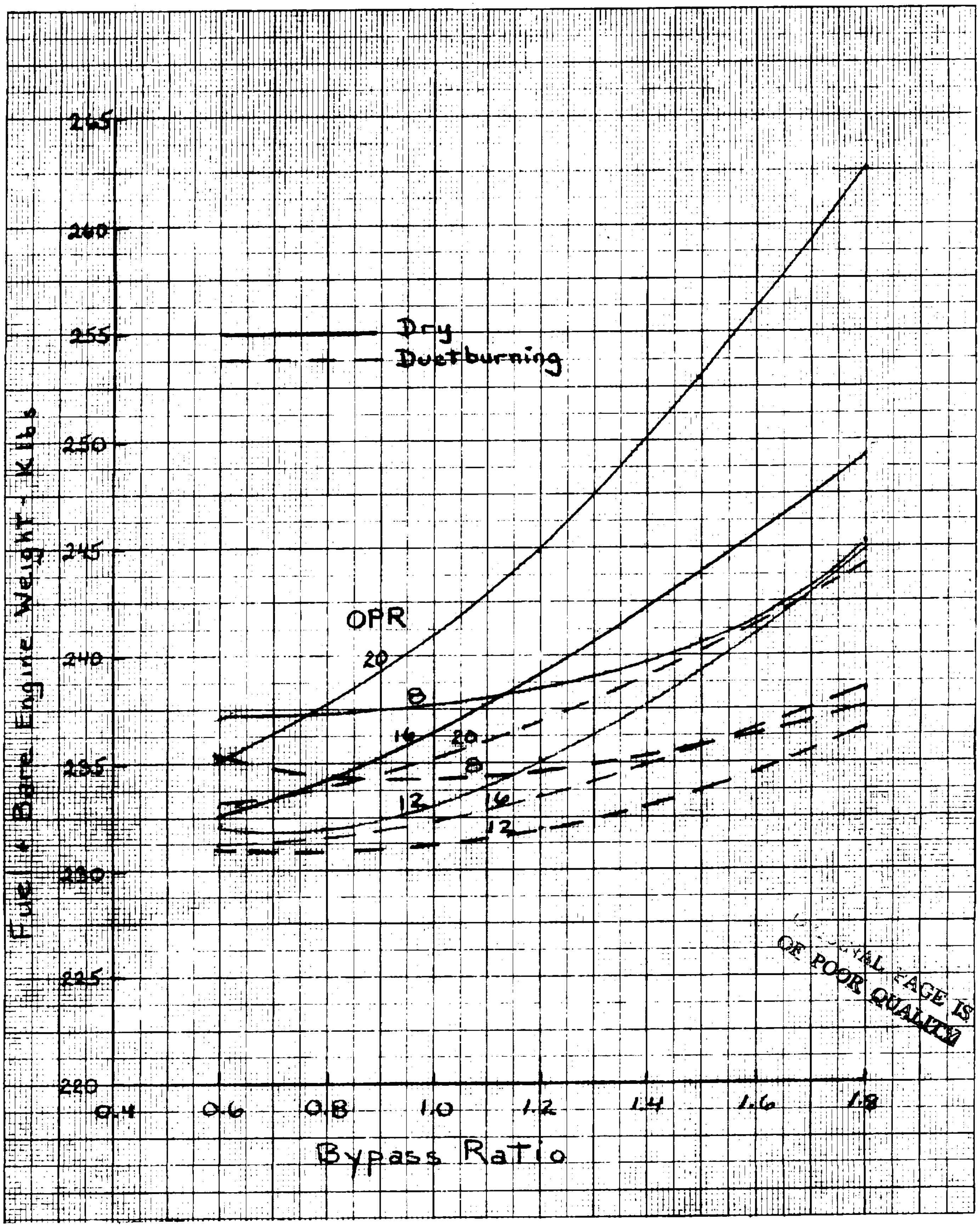

Fig. 5: Sum of Engine Plus Fuel Weight. 20000 lb. thrust engines.

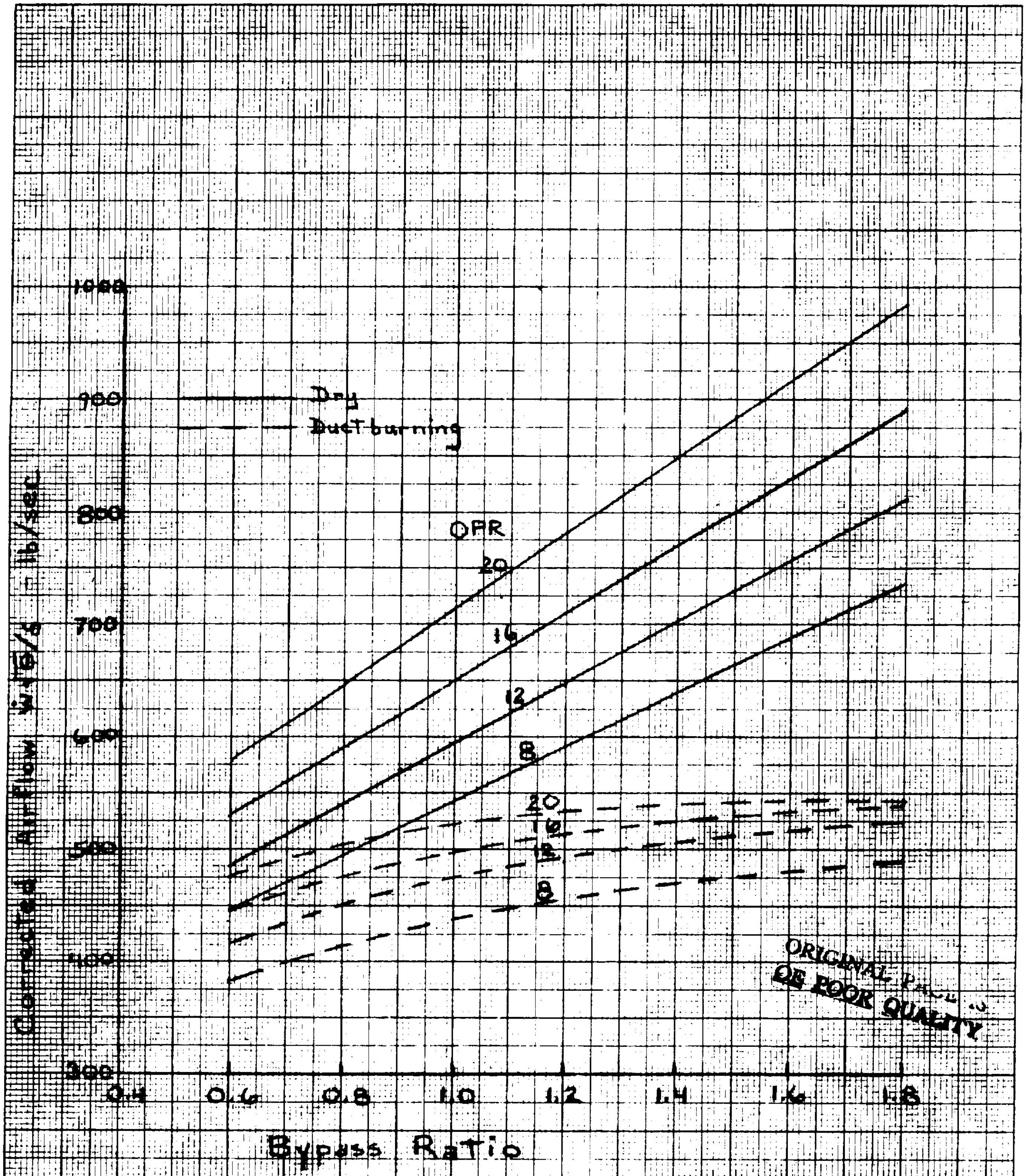

Fig. 6: Corrected Airflow Required. 20000 lb. thrust engines, Optimum Fan Pressure Ratio and Ductburner Temperature Rise.

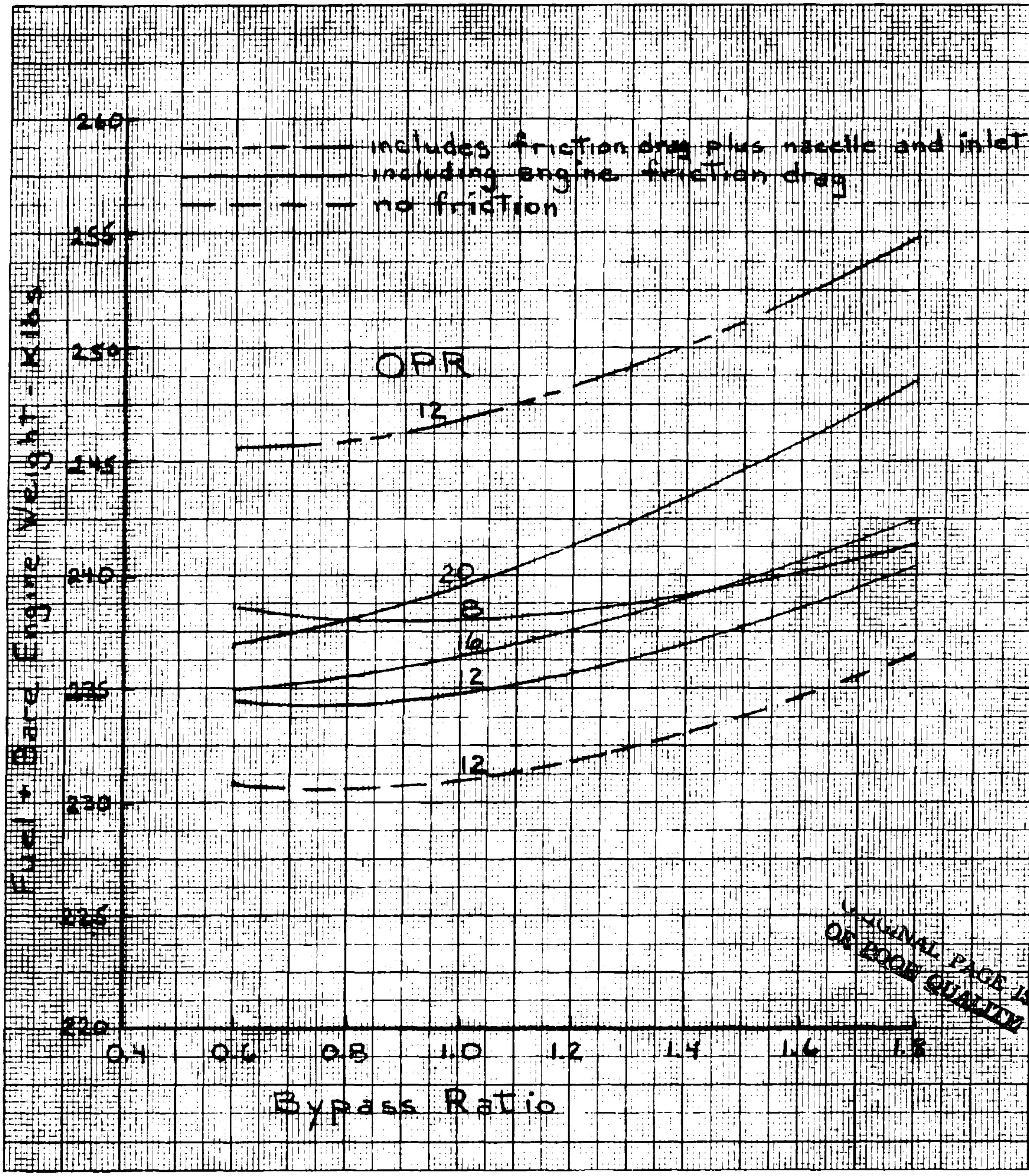

Fig. 7: Effect of Engine Friction Drag on Fuel Plus Bare Engine Weight.

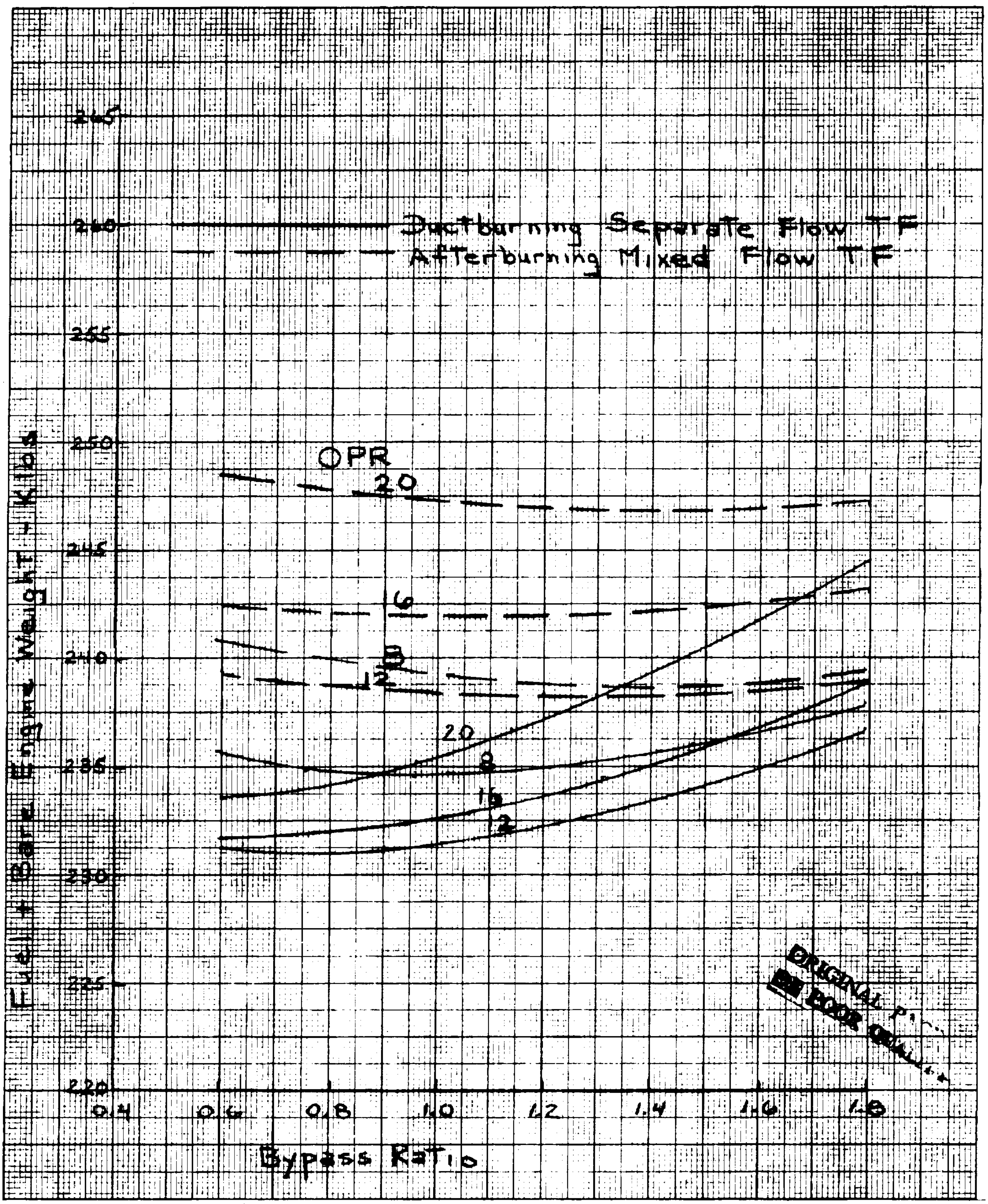

Fig 8.: Comparison of Ductburning Separate Flow Turbofan with Mixed Flow Afterburning Turbofan.

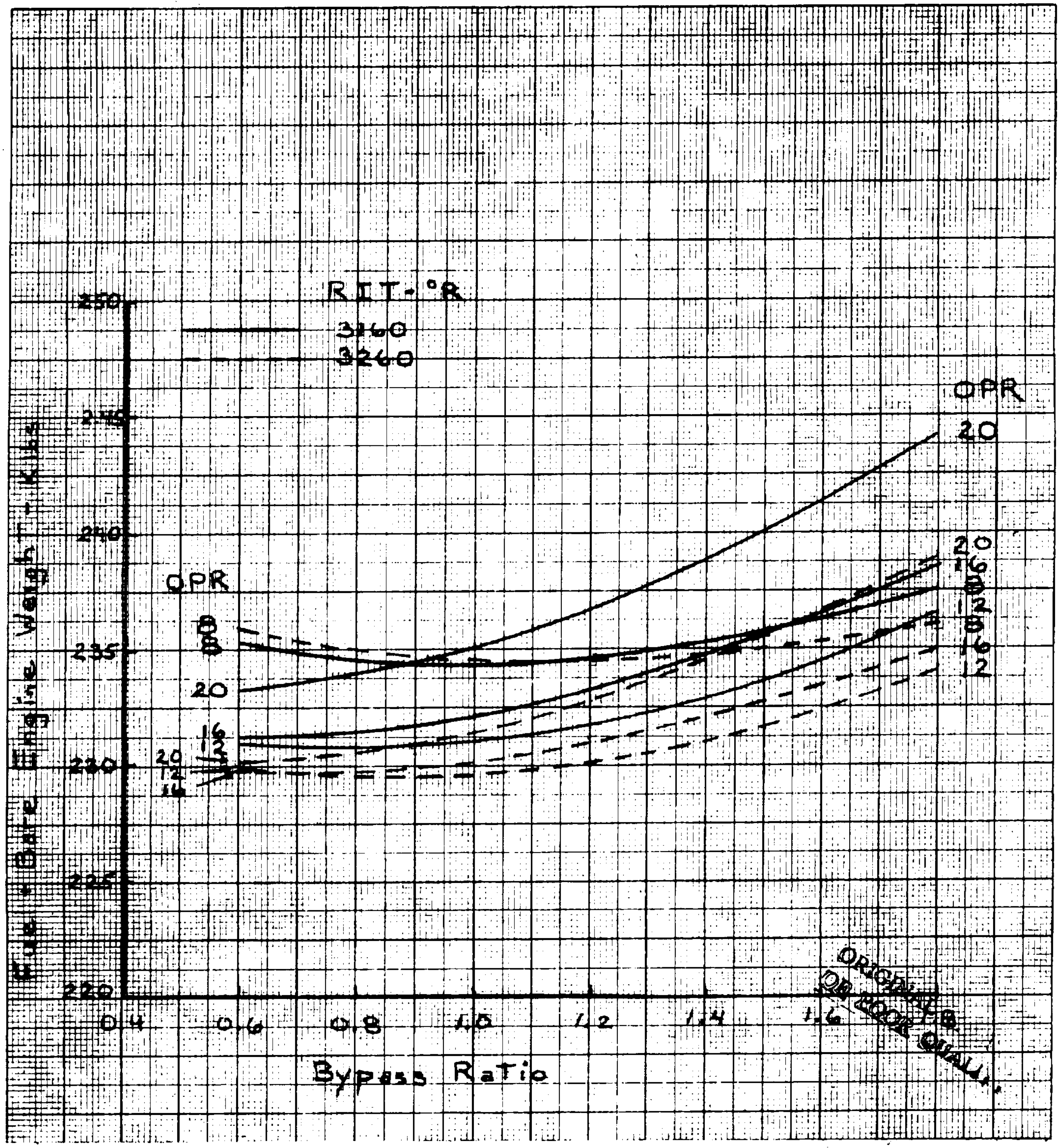

Fig. 9: Effect of Turbine Rotor Inlet Temperature on Ductburning Turbofan Performance.

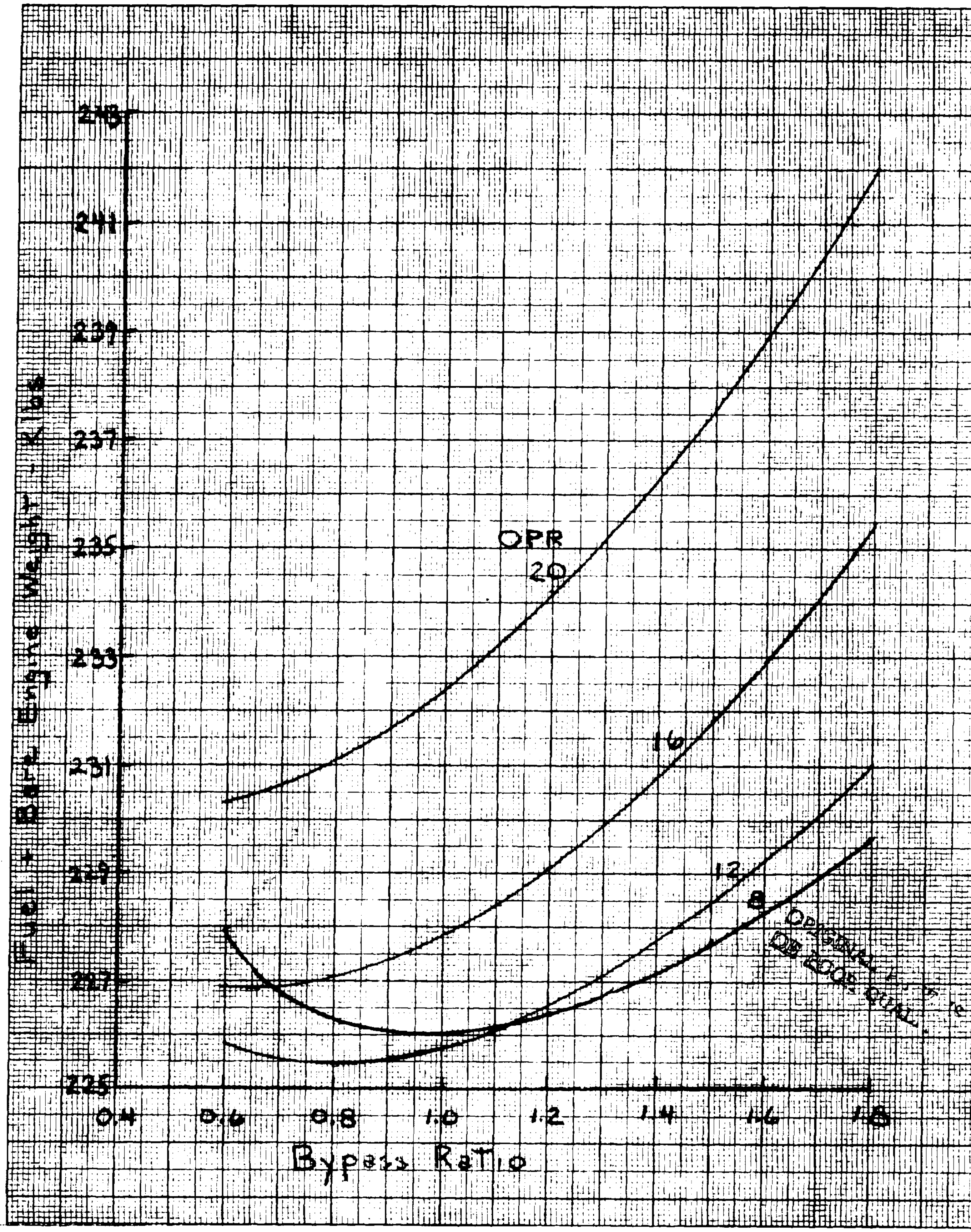

Fig.10: Sum of Engine Plus Fuel Weight. Mach 2.0, 54000 ft., 18500 lb. thrust engines, Ductburner Temperature Rise and Fan Pressure Ratio optimized.

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16. Abstract
A study has been made of the effect of engine overall pressure ratio, fan pressure ratio, and ductburner temperature rise on the engine weight and cruise fuel consumption for a Mach 2.4 Supersonic Transport. A practical engine must be designed to accomodate all of the mission requirements, including for example off-design operation at takeoff with noise constraints and subsonic cruise. However, this study is limited to consideration of design-point engines that are optimized purely for the supersonic cruising portion of the flight, where the bulk of the fuel is consumed. The purpose of the study is to provide an idealized benchmark against which more-practical engines can be measured. This study concludes that, based on constant thrust requirements at cruise, (fixed gross weight and aerodynamics), fuel consumption considerations would favor medium-bypass ratio engines (1.5 to 1.8) of overall pressure ratio of about 16. Engine weight considerations favor low bypass ratio (0.6 or less) and low overall pressure ratio (8). Combination of both effects result in bypass ratios of 0.6 to 0.8 and overall pressure ratio of 12 being the overall optimum. In addition, ductburning is shown to be significant in reducing engine weight with acceptable fuel consumption penalties.

17. Key Words (Suggested by Author(s))
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